Determination of heavy quark non-perturbative parameters from spectral moments in semileptonic B decays

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The CKM matrix element $|V_{cb}|$ has been accurately determined at DELPHI. This has been possible by measuring moments of the hadronic mass distribution and of the lepton energy spectrum in inclusive B semileptonic decays, $B \to X_c \ell \nu$. In addition, production and decay properties of the most uncertain component of the hadronic system X_c, namely the D** states, have been obtained. Results yield to some theoretical contradictions.

International Europhysics Conference on High Energy Physics
July 21st - 27th 2005
Lisboa, Portugal

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[†]A footnote may follow.

1. Introduction

The most precise determination of the CKM matrix element $|V_{cb}|$ lies in measuring parameters entering in the theoretical expression of the inclusive semileptonic (sl) decay width of B hadrons [1]. Since the inclusive semileptonic branching fraction and the B meson lifetime have been measured with high accuracy[1] one would expect to extract $|V_{cb}|$, from the value of the inclusive sl decay width, with an experimental uncertainty below 1%. However, the theoretical expression of the inclusive sl decay width, from which one extracts the CKM matrix element, depends on the b and c quark masses and on parameters describing the non-perturbative physics of the process. These parameters are poorly constrained by the theory. They are the expectation value of the kinetic energy of the b quark inside the hadron, μ_π^2, and the Darwin parameter, $\tilde{\rho}_D^3$[2]. A way to improve the $|V_{cb}|$ determination consists thus in experimentally accessing to these parameters. By measuring moments of inclusive observables such as the moments of the energy spectrum or of the hadronic mass distribution in B$\to X_c\ell\nu$ decays, one can extract them with high accuracy.

2. Measurement of moments

At DELPHI, moments up to third order of the hadronic mass distribution and of the lepton energy spectrum in inclusive B$\to X_c\ell\nu$ decays have been measured [3]. The most important advantage of measuring the moments at the Z energy is that one has access to nearly all the lepton energy spectrum. Moments of the hadronic mass distribution have been obtained by measuring the mass distribution in $\overline{\mathrm{B}^0} \to \mathrm{D}^{**}\ell^-\overline{\nu}$ decays. According to the Heavy Quark Effective Theory [4], the hadronic system X_c is expected to be composed of several spin doublets consistent with different configurations of spin and orbital angular momentum of the light and heavy quarks inside the heavy meson. The ground state, with angular momentum L=0, corresponds to the D and D* mesons. They account for about 70% of the total inclusive B sl decay width and their properties are well established [5]. For L=1 two different doublets appear, with $j_q = \frac{1}{2}$ and $j_q = \frac{3}{2}$, corresponding to two broad ($\mathrm{D}_0^*, \mathrm{D}_1^*$) and two narrow ($\mathrm{D}_1, \mathrm{D}_2^*$) resonances respectively. The orbital L=1 resonances and any other possible state, such as higher orbital angular momentum systems, non resonant $\mathrm{D}^{(*)}\pi(\pi)$ contributions or radial excitations, are generically called here D** states. Since the masses and relative branching fractions of the D and D* mesons (p_D and p_{D^*} respectively) are well known, one can measure the moments of the total hadronic mass distribution by measuring the mass distribution of the D** system. That is, through $< m_{X_c}^n >= p_D m_D^n + p_{D^*} m_{D^*}^n + p_{D^{**}} < m_{D^{**}}^n >$, n being the order of the hadronic mass moment. At DELPHI, the D** signal has been reconstructed into the $\mathrm{D}^0\pi^+$, $\mathrm{D}^+\pi^-$ and $\mathrm{D}^{*+}\pi^-$ decay channels. Wrong sign combinations have allowed to limit the $\mathrm{D}^{(*)}\pi\pi$ contribution below 0.22%. Figure 1 shows the fitted $m_{\mathrm{D}^{**}}$ distribution obtained by DELPHI. The distribution is compared with the CDF data measured in [6].

[1] The inclusive sl branching fraction has been measured both at LEP experiments and at the $\Upsilon(4S)$ energy. Results agree and the average, after properly correcting by the contribution of the several b-species at LEP, gives $\mathcal{B}$(B$\to X\ell\nu$)=(10.92 $\pm$ 0.13)%. The B meson lifetime has been measured to be τ_B=1.568 $\pm$ 0.009 ps [2]

[2] Two more parameters are entering in the expression, up to third order in a $1/m_b$ expansion, namely the expectation value of the chromomagnetic operator, μ_G^2, and the spin-orbit expectation value, ρ_{LS}^3. The value of the former is constrained by the mass splitting between the B* and the B mesons. The inclusive sl decay width is quite insensitive to the value of the latter.

The values of the hadronic mass moments and of the moments of the lepton energy spectrum, measured also at DELPHI [3], have been combined in a fit to extract the non-perturbative parameters entering in the expression of the inclusive sl decay width. From the fitted values one obtains an accurate determination of the $|V_{cb}|$ matrix element: $|V_{cb}| = 0.0421 \times (1 \pm 0.014 \pm 0.014 \pm 0.015)$, where the two first errors are coming from the experimental determination of the sl decay width at LEP and of the non-pertubative parameters at DELPHI, respectively, and the last is coming from the remaining theoretical uncertainties in the $|V_{cb}|$ extraction. It is also important to remark the success of the theory and the agreement between the measured moments obtained from different experiments [7].

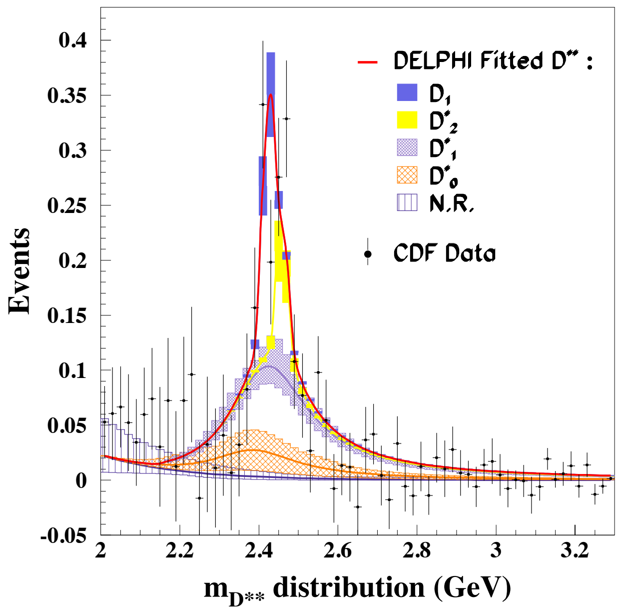

Figure 1: *Comparison between the fitted results from DELPHI of the* D^{**} *mass distribution and the data measured by the CDF experiment [6] normalized to the DELPHI histogram.*

3. The $\frac{1}{2} > \frac{3}{2}$ puzzle

In spite of the good agreement of the measured hadronic mass moments, still some unknows remain unresolved. In particular, when one substracts the D and the D* contributions from the inclusive B sl branching fraction [5], one gets $(2.9 \pm 0.3)\%$[3] for D^{**} states (with L=1, higher L or any other resonant or non-resonant state). The $\mathrm{D}^{**}\ell\nu$ rate measured by DELPHI is $(2.7 \pm 0.7 \pm 0.2)\%$, almost saturating the inclusive sl branching ratio. The BELLE experiment has measured that the $\mathrm{D}^{(*)}\pi\ell\nu$ contribution to the total $\mathrm{D}^{**}\ell\nu$ rate is below 2%, suggesting a large $\mathrm{D}^{(*)}\pi\pi$ component. Nevertheless, this is in contradiction with ALEPH [8] and DELPHI [3] results. On the other hand,

[3] Numbers have been normalized to the sl branching fraction for the B^0 meson.

the narrow component of the D** system has been measured by different experiments [8, 9], and accounts for about one third of the total D$^{**}\ell\nu$ rate. This implies a large contribution of broad resonances as it has been observed by DELPHI. However, theoretical predictions based on QCD sum rules and some specific quark models state a large dominance for L=1 narrow states ($j_q = \frac{3}{2}$) over broad ($j_q = \frac{1}{2}$) states, in apparent contradiction with the experimental results[4].

4. Conclusions

Measurement of moments of the lepton energy spectrum and of the hadronic mass distribution in b-hadron sl decays provide a way to accurately determine the $|V_{cb}|$ matrix element as it has been performed at DELPHI. In addition, results between different experiments and the theory are in an impressive agreement. Nevertheless, an apparent contradiction between theory and experiment, concerning the D** composition and rates is still quite puzzling. Further and more accurate studies should be carried out at B factories and at hadron colliders, which benefit from a large D** statistics, to provide a comprehensive answer.

5. Acknowledgements

Part of this work has been supported by the European Community FP6 Marie Curie Mobility Actions, Contract No. MEIF-CT-501178. I would like to thank I. Bigi, A. LeYaouanc, L. Oliver, O. Pène and P. Roudeau for the helpful discussions at Orsay.

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[4] In practice it is also possible to have broad state contributions different from L=1 states.